

Demonstrations of magnetic phenomena: Measuring the air permeability using tablets

V.O.M. Lara,^{1,2,*} D. F. Amaral,³ D. Faria,¹ and L. P. Vieira⁴

¹*Instituto de Física - Universidade Federal Fluminense, Niterói - Rio de Janeiro Brazil*

²*Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro, São Gonçalo - Rio de Janeiro Brazil*

³*Consórcio de Ensino à distância do Rio de Janeiro (CEDERJ), São Gonçalo - Rio de Janeiro Brazil*

⁴*Instituto de Física - Universidade Federal do Rio de Janeiro, Rio de Janeiro - Rio de Janeiro Brazil*

(Dated: May 27, 2014)

Abstract

We use a tablet to determine experimentally the dependencies of the magnetic field (B) on the electrical current and on the axial distance from a coil (z). Our data shows a good precision on the inverse cubic dependence of the magnetic field on the axial distance, $B \propto z^{-3}$. We obtain with good accuracy the value of air permeability μ_{air} . We also observe the same dependence of B on z when considering a magnet instead of a coil. Although our estimates are obtained through simple data fits, we also perform a more sophisticated error analysis, confirming the result for μ_{air} .

PACS numbers:

The use of tablets and smartphone in science education expands possibilities for approaches that motivate students to understand better several physical phenomena[1–4]. In particular, tablets were shown as good tools to measure magnetostatic responses in current-carrying wires. This interesting work is about magnetic field sensing [1]. It reports a simple way of obtaining experimentally the linear dependence between the magnetic field B and the number of turns N in the current-carrying coil using an "app" for iPad [5]. However, additional dependences of B are still not discussed, some of which we show in this paper leading to a wider description of this kind of system.

We determine the dependencies of B on the electric current I and on the axial distance z in a coil, in suitable conditions using an iPad and the same free app MagnetMeter [5] (we suggest a similar app for Android [6]). We also perform the similar experiments with a small magnet instead of a coil. For the coil, we also make a good estimate for the magnetic permeability of the air $\mu_{air} \cong \mu_0 \equiv 4\pi \times 10^{-6} \text{ Hm}^{-1}$.

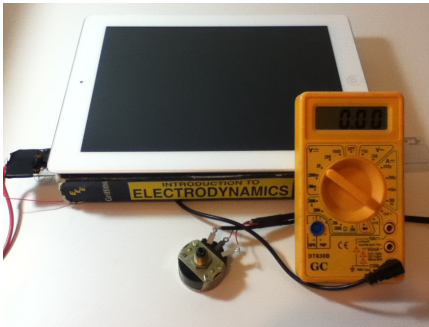


FIG. 1. (Color online) Photography from the experimental setup.

The demonstration set used is composed by an electrical circuit, a ruler and a book. The circuit is formed by the following components, all of them connected in series: a wirewound potentiometer with resistance up to 30Ω ; a resistor with 10Ω ; an electrical source from a cell phone (max. output current $\sim 0.9\text{A}$); a digital multimeter and a coil (internal diameter $2R_i = 1.91 \text{ cm}$ and external diameter $2R_e = 2.42 \text{ cm}$ and $N = 62$ turns).

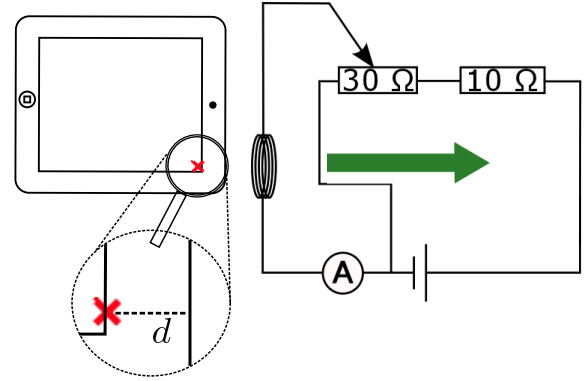


FIG. 2. Schematic representation of the coil experiment. The red cross indicates the magnetometer position inside the iPad, while the green arrow corresponds to the z axial displacement of the coil.

Next, we describe the circuit assembly, which is relatively easy to build. This circuit is formed in such a way that the potentiometer enables the variation of the current in the coil, which is measured by the ammeter. However, for safety issues, it could also be necessary to add the extra resistance of 10Ω to avoid high currents. The potentiometer has three terminals. The middle one has to be connected to the coil, while each one of the other terminals are connected to the resistor and to the negative source terminal, as it can be seen in figure 2. There is no need to worry about the connection order of these two terminals, because the circuit should behave

* V.O.M. Lara: vitor.lara@ifrrj.edu.br

as expected in both ways. Although, one should be careful about the direction in which the potentiometer will increase the current value measured by the ammeter.

As a standard procedure throughout, before starting the experiment we press the red button on the Magnetometer app in order to set any other relevant magnetic interferences aside, such as the Earth's magnetic field. In the first experiment we pulled the coil up close to the iPad upper right edge (see figure 2). We fixed the axial distance between the coil and the magnetometer at $z = 4.8 \text{ cm}$. It is crucial that one takes into account the distance d relative to the localization of the magnetic sensor inside the iPad, adding it to the value measured by the ruler (for the iPad we use $d \sim 1.8 \text{ cm}$ [7]). Next we increase the current by equal amounts $\delta I = 0.05 \text{ A}$, writing down the magnetic fields measured by each correspondent current, as plotted in figure 3. The data adjust was realized using the 'fit' command from the *Gnuplot*[8], with

$$\begin{aligned} B(I) &= aI + b, \\ a &= (41.0247 \pm 0.2571) \mu\text{T/A} \quad \text{and} \\ b &= (0.611347 \pm 0.143) \mu\text{T}. \end{aligned} \quad (1)$$

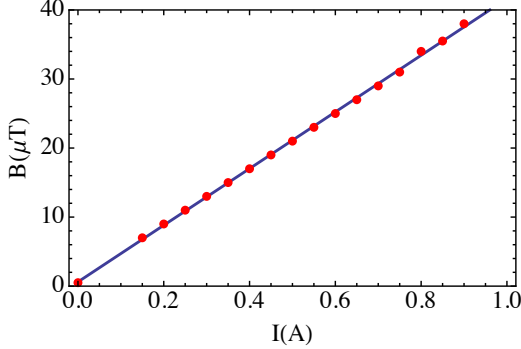


FIG. 3. (Color online) Magnetic field linear dependence on the electric current for the coil. The blue line represents the linear fit and the red points correspond to the obtained data. The values of a and b vary according to the coil radii and to the axial distance from the magnetic sensor.

The second experiment consists of an analysis of the magnetic field dependence on z for both the coil and the magnet. We start by holding the ruler between the book pages and positioning the iPad above the book with its magnetic sensor facing the coil or the magnet. For the coil we increase the current up to its maximum $I \sim 0.9 \text{ A}$, which is not necessary in the case of the magnet due to its permanent magnetization. We subsequently move the coil (magnet) by equal displacements in the green arrow direction as indicated in figure 2. We take notes of the magnetic field showed by the app for each distance. In figure 4 we plot the experimental data of B as a function of z obtained by the Demonstration Set for (a) the coil

(see Table II) and (b) the magnet, respectively. In addition, we perform a data fit using $B(z) = az^b$, as shown in table I. For both cases we obtain an excellent agreement with the expected z^{-3} dependence [9].

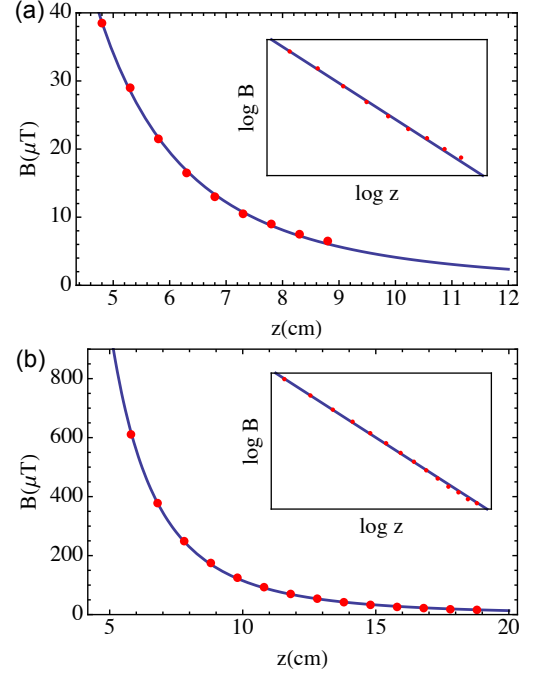


FIG. 4. (Color online) Magnetic field versus distance for the (a) coil and (b) magnet. The inset shows the same data on log log scale.

TABLE I. Magnetic field fitting, $B(z) = az^b$ for the coil and for the magnet.

Parameters	$a \pm \delta a$	$b \pm \delta b$
Coil	4624.6 ± 307.4	-3.05112 ± 0.03917
Magnet	142012 ± 2903	-3.09232 ± 0.01217

We present in figure 5 the dimensions of the coil used. From figure 5 one finds $R_M = (1.910 + 2.440)/4 \text{ cm} = 1.088 \text{ cm}$, where R_M is the mean radius of the coil. We also know the electrical current value and the number of turns of the coil. These informations allow one to obtain an estimation for the magnetic permeability $\mu_{air} \cong \mu_0$. The inverse cubic dependence of the magnetic field for the coil is consistent with the magnetic field generated by a pure magnetic dipole (m) in its axis[9], given by

$$\vec{B}(z) = \frac{\mu_0}{2\pi} \frac{m}{z^3} \hat{z}, \quad (2)$$

where $m = NI\pi R_M^2$, $N = 62$ turns, $I = 0.9 \text{ A}$ and R_M is the mean radius of our coil. Therefore, we impose $b = -3$ for our data and we leave a' as the only parameter in the data fit. The data fit performed for the points

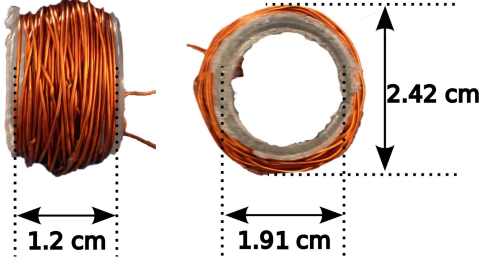


FIG. 5. (Color online) Spatial dimensions of the coil used in this work. Notice that the coil width is 1.2 cm, we use its half width as the referential point to measure the distance z from the magnetic field sensor. The inner and outer diameter are 1.910 cm and 2.440 cm, respectively.

displayed in figure 4 returns $a' = 4240 \pm 25.81$, with a standard deviation less than 1%. The relation between the a' coefficient for the coil and μ_{air} is given by

$$\mu_{air} \cong \frac{a'2\pi}{m} = \frac{2a'}{NIR_M^2} . \quad (3)$$

Converting all the units to their SI values, the result leads to $\mu_{air} \cong 1.298 \times 10^{-6} Hm^{-1}$, in good agreement with the expected value of $\mu_0 \equiv 4\pi \times 10^{-6} \approx 1.2566370614 \times 10^{-6} Hm^{-1}$.

Although this estimation for μ_{air} is already good enough, we also perform another procedure to evaluate the air permeability and the error analysis.

TABLE II. Magnetic field $B(z)$ and z for the coil.

Magnetic field (B) [μT]	Axial distance (z) [cm]
38.5	4.8
29	5.3
21.5	5.8
16.5	6.3
13	6.8
10.5	7.3
9	7.8
7.5	8.3
6.5	8.8

We use the coil data points from Table II, and we replace these values in equation 2 in order to find the value of μ_{air} for each single point. We also consider the following uncertainties in the experimental measurements: $\delta B = 0.5 \mu T$, $\delta I = 0.01 A$, $\delta z = 0.001 m$, $\delta N = 1$ and $\delta R_M = 0.00005 m$. There is a precision difference between R_M and z because we used different measurement devices. For z we use a simple ruler, and for R_M we use a calliper rule. For the error calculation we use the following variance formula taking into account all the independent variables [10]:

$$\sigma_{\mu_{air}} = \sqrt{\left(\frac{\partial \mu_{air}}{\partial B}\right)^2 \delta B^2 + \dots + \left(\frac{\partial \mu_{air}}{\partial R}\right)^2 \delta R^2} . \quad (4)$$

Each partial derivative of the previous expression is evaluated at the average values of magnetic field and of axial distances, in such a way that we obtain the same uncertainty value for all the points, as a mean value. The uncertainty $\sigma_{\mu_{air}} = 0.1 \times 10^{-6} Hm^{-1}$ tell us that the experiment enables the evaluation of μ_{air} with 2 significant figures. We show in Fig. 6 the μ_{air} values obtained for different axial distances, given by red dots with correspondent uncertainties. The expected value of μ_{air} is also exhibited in the figure given by the blue line. Notice the relatively small data deviations from the expected value, which means that following this procedure, we also obtained a fair estimate for μ_{air} .

Unfortunately, in this experiment analysis it was not possible to determine the value of μ_{air} using the magnet. In fact, all that one is able to make is an estimate for the magnet magnetic dipole m , assuming the value for μ_{air} .

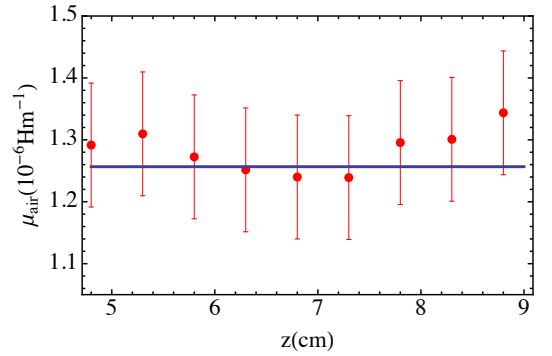


FIG. 6. (Color online) Air permeability values obtained from the experimental data evaluated at different axial distances (red points). The blue line indicated the established value for μ_{air} .

From the circuit made we obtained a linear dependence between B and I . In addition, we observed the same proportionality $B \propto z^{-3}$ for both the coil and the magnet, enabling one to discuss the parallel between them. Finally, we also could make a fair and simple estimate for the magnetic permeability μ_{air} , even under the limitations of our experimental device. Unfortunately, in our analysis applied to the magnet does not give the value of μ_{air} . In the magnet case, all we can do, assuming the value for μ_{air} , is an estimate for its magnetic dipole m . For further experiments we suggest the study of the magnet dependence on distance for other geometries, like the long straight wire or the current on a plane sheet of steel.

ACKNOWLEDGEMENTS:

This work was partially supported by CNPq and CAPES (Brazilian Government Agencies).

-
- [1] N. Silva, *Magnetic field sensor*, The Physics Teacher 50, **372**, 2009.
 - [2] L. Vieira and V. O. M. Lara, *Macro photography with a tablet: applications on Science Teaching*, Revista Brasileira de Ensino de Física, v. 35, n. 3, 3503 (2013).
 - [3] L. Vieira, D. F. Amaral and V. O. M. Lara, *Standing sound waves in a tube: analysis of problems and suggestions*, Revista Brasileira de Ensino de Física, v. 36, n. 1, 1504 (2014)
 - [4] L. P. Vieira, *Physics Experiments with Tablets and Smartphones*, Physics Institute of UFRJ, Master Thesis, 2013.
 - [5] MagnetMeter homepage at App Store <https://itunes.apple.com/us/app/magnetmeter-3d-vector-magnetometer/id346516607?mt=8>, Accessed: 16/02/2013
 - [6] Smart Tools homepage at Google Play <https://play.google.com/store/apps/details?id=kr.aboy.tools>, Accessed: 16/02/2013
 - [7] To determine the inner distance d we use a needle. As the needle is ferromagnetic, it will influence the magnetometer. Strolling with the needle tip on the screen, the position in which the magnetic field is at his maximum should be the location of the magnetometer inside the tablet or phone.
 - [8] Gnuplot <http://www.gnuplot.info/>
 - [9] D. J. Griffiths, "Introduction to Electrodynamics", Prentice-Hall, 2010.
 - [10] H. H. Ku, "Notes on the use of propagation of error formulas", Journal of Research of the National Bureau of Standards (National Bureau of Standards) 70C (4), (October 1966).